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Origins of Acrylic Plastic Submersibles

J. D. Stachiw

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THE ORIGINS OF ACRYLIC PLASTIC SUBMERSIBLES

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ABSTRACT

The research submersible NEMO, launched and certified in 1970 by the U.S. Navy, represents the first seaworthy, deep diving, one atmosphere environment, diving system which utilizes a pressure hull fabricated from transparent acrylic (polymethyl methacrylate) plastic. Its pressure hull is the culmination of (1) research into the structural performance of acrylic plastic spherical shells under long term cyclic external pressure loading, (2) development of economical fabrication techniques for acrylic plastic spheres with uniform curvature and thickness. Since the launching of NEMO many other submersibles with acrylic plastic pressure hulls have been built and successfully operated in the 0 to 3270 feet (0 to 1000 meter) depth range.

INTRODUCTION

Although men have been diving in the oceans since time immemorial, they were doing it either for food, pearls, sponges, or shipwrecked treasures. It is only recently however, that a concerted effort has been made to explore the ocean and exploit its riches by having scientists and engineers descend into hydrospace, protected from the hostile environment by one atmosphere enclosures with life supporting environment.

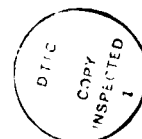
The fearless explorers that pioneered in this area were William Beebe (Reference 1), Otis Barton (Reference 2) and Auguste Piccard (Reference 3). At great personal risk and expense they developed in the short time span between 1930 to 1950 bathyspheres and bathyscaphs that allowed them to descend several thousand feet into the ocean and observe salt water animals never described before (Figure 1). Their observations were, however, limited by the small size of

viewports incorporated into pressure resistant opaque metallic hulls of their bathyspheres and bathyscaphs (three viewports with 6 inches inside diameter in Barton's Bathysphere, and a single 4 inches inside diameter viewport in Piccard's Bathyscaph TRIESTE).



Figure 01 Otis Barton's Benthoscope with two 6 in. inside diameter fused quartz viewports in which he successfully dove to 4500 feet depth offshore California during 1949.

The explorers who followed in the pioneers footsteps had at their disposal submersibles that were significantly more agile, and comfortable. Furthermore, they were equipped with manipulators that scientists could use to collect mineral and live specimen for further study in their shipboard laboratories. Still, the size of the viewports had remained approximately the same from 1950 to 1970, as the shape of



A-1

viewports and materials used in their construction remained unchanged since the days of Beebe, Barton and Piccard. This bottleneck in pressure hull design for diving systems had to be eliminated if exploration of hydrospace had to proceed beyond the operational constraint set by individual viewports with less than 90 degree field of vision for a single observer.

Attempts were made to overcome this limitation by brute force approach; the number of viewports in pressure hulls proliferated, each covering a small field of view around the bow of the submersible. Unfortunately, this did not resolve the problem, as the scientist's field of view through his viewport did not overlap the pilot's field of view through the pilot's viewport, or vice versa. Ultimately it dawned upon the vehicle designers that this problem could be resolved satisfactorily only by making either a large section, or the complete pressure hull from a transparent material. In a pressure hull fabricated totally, or partially, from a transparent material both the pilot and the scientist, or several scientists would be viewing together the same panorama outside the vehicle, and direct the pilot from the comfort of their contoured seats to gather specimens outside the hull.

A practical solution to this problem required the availability of (1) inexpensive, transparent material with reliable engineering properties, (2) proven designs of entire pressure hulls, or their components from a transparent material with predictable structural performance, and (3) economical procedures for fabrication of entire pressure hulls, or large sections thereof from transparent material. In the search for such material the attention immediately focused on glass and polymethyl methacrylate (acrylic plastic) because of their (1) optical clarity in thick sections and (2) low intrinsic cost (References 4 and 5). It did not take very long, however, before massive glass was eliminated from further consideration as construction material for large, panoramic visibility viewports, or complete pressure hulls.

The reason for it were both of engineering and economic nature. Massive glass was found to be very sensitive to internal flaws and surface imperfections, making it very expensive to devise a quality assurance program that would qualify it for service as structural components in pressure hulls of diving bells, habitats or submersibles. Furthermore, the cost of fabricating large, high quality massive glass components with optical surface finish was found to be beyond the reach of individual entrepreneurs or oceanographic research institutions with meager budgets. And thus, unless the U. S. Congress was willing to create a new agency for exploration of hydrospace with a budget matching that of NASA, massive glass for undersea structures would remain forever a desirable wonder material, outside the scope of consideration for designers of manned submersibles.

By the middle of nineteen sixties it became apparent that the US Congress was not favorably disposed to creation of such an agency and that the required funding would not be forthcoming from other potential sources (i.e. U. S. Navy, or large glass companies like Corning Glass etc). Based upon the above realistic evaluation of the situation private entrepreneurs, oceanographic research institutions and Navy laboratories directed their attention to clear acrylic plastic as the potential structural material for undersea vehicles with panoramic visibility.

With the shift in focus from glass to acrylic plastic as the potential structural material came also a change in the projected operational scope for the undersea vehicles. Instead of concentrating on the scientific exploration of abyssal depths and establishing dive records the objective shifted to exploitation of the continental shelves for economic, or defense purposes. The scene was now set for the appearance of a new generation of submersibles that would extensively utilize acrylic plastic in their construction, so that the crews would utilize fully their sense of vision in the performance of scientific and engineering tasks.

EARLY EXPERIMENTS WITH ACRYLIC STRUCTURES

When the attention of ocean engineers began to focus on acrylic plastic as the potential structural material for undersea vehicles with panoramic visibility the state of technology encompassing massive acrylic plastic was in its infancy.

Supply of massive acrylic plastic was limited to 4 inches thick x 48 x 60 sheets cast from monomer resin between glass plates, and there was very little hope for the availability of thicker, or larger sheets as the duration of monomer resin polymerization process rapidly became uneconomical for thicker sheets.

The strength of massive acrylic plastic under cyclic and long term compressive loading was not defined in terms of allowable design stresses, as up to this time massive acrylic plastic has not been utilized in structures under cyclic compressive loading.

The structural performance of spherical pressure hulls made from massive acrylic plastic was not understood, particularly the (1) effect of creep upon elastic stability of shell structures and the (2) recuperation of the material after removal of the hydrostatic pressure from the shell.

The fabrication of spherical shells was limited to free forming of small hemispheres with compressed air from thin acrylic sheets. The small sizes of available sheets in thickness over 2 inches, and uneven reduction in thickness during the free forming process limited the maximum size of spheres to less than 60 inches, and actual wall thickness to less than one inch.

The early acrylic pressure hulls for diving systems were severely restricted in size and depth because of the immature state of massive acrylic plastic technology. And

yet, even with all their structural and operational limitations the first acrylic spheres built for diving systems displayed to the ocean engineering community the advantages of panoramic vision from one atmosphere pressure hulls for diving systems.

For the first time in the history of ocean exploration the occupants of one atmosphere diving systems could utilize their sense of vision unhampered by opaque enclosures and thus maximize the operational value of the dive duration. The diving systems with the all-acrylic pressure hulls, which demonstrated to the ocean engineering community the potential of panoramic visibility were HIKINO, KUMUKAHI, and NUCOTE.

HIKINO was conceived in 1962 by the late Dr. W. McLean and engineered by D. K. Moore of Naval Ordnance Test Station, China Lake, CA. The two-person vehicle had the shape of a catamaran with the acrylic sphere suspended between the two hulls (Figure 2). Flooding of ballast tanks in the catamaran hulls controlled the buoyancy of the vehicle. Cycloidal propellers mounted on the catamaran hulls provided the vehicle with mobility along three axis of travel. The acrylic sphere itself was assembled from two hemispheres mated at the equator to a metallic joint ring. A clamshell arrangement allowed ingress and egress from the sphere by its crew.

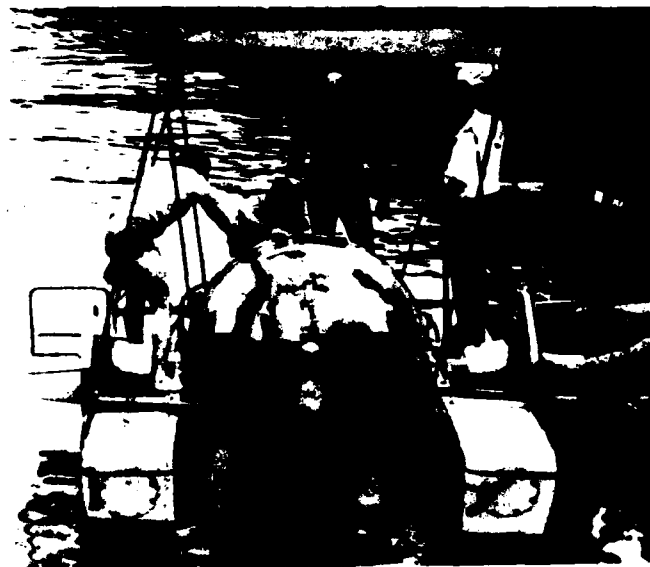


Figure 02. Dr. W. McLean's HIKINO, the first concept of an submersible with panoramic visibility undergoing pierside testing during 1965.

The vehicle demonstrated successfully the design concept of panoramic visibility and triaxial mobility. However, because of thin spots in the free formed acrylic hemispheres their design depth was less than 20 feet, and because of it the operation of the vehicle was restricted to reservoirs and lakes with less

than 20 feet depth. As a result of its severe operational depth limitation HIKINO was subsequently used only as a concept demonstrator. It was never certified by the Navy and finished its career as a museum display.

KUMUKAHI was conceived in 1967 by T.A. Prior, engineered by W. R. Forman, fabricated by Fortin Plastics, and delivered to Oceanic Institute of Hawaii in September 1969 (Reference 6). The 3700lb submersible was configured as a self propelled diving bell with the batteries and a variable displacement tank contained in a pod suspended directly under the sphere (Figure 3). The 56 inch OD acrylic pressure hull was fabricated by thermoforming 1.25 inch thick acrylic sheets into flanged spherical quadrants inside a female/male mold assembly. The use of a clamped mold assembly resulted in a thickness reduction of only 8 percent at the center of each sector. The quadrants were subsequently bonded together with acrylic adhesive, an opening was cut out at the top of the sphere, and the edge of the opening was reinforced with adhesive impregnated glass fiber tape. An acrylic spherical hatch cover, whose edges were also reinforced with adhesive impregnated glass fiber tape completed the spherical hull. Six electric motor driven propellers provided the vehicle with triaxial mobility at approximately 1 knot.



Figure 03. KUMUKAHI the first acrylic plastic submersible to perform open sea dives in 1967.

KUMUKAHI experienced extensive manned operational evaluation at snorkel diver depth, and unmanned structural testing to 350 and 450 feet depths in the open sea off Pokai Bay on Oahu Island. The recorded strains indicated that there was no permanent deformation in the 0 to 350 feet depth range during 10 successive 30 minutes long dives, and therefore the pressure hull appeared to be safe for manned dives to 300 feet. Unfortunately, at the completion of the 6 hour long unmanned proof

test dive to 450 feet the submersible was smashed against the support ship and the acrylic pressure hull damaged. After repair to the pressure hull the submersible saw some limited service to 90 feet, however it was never certified by the Navy, or American Bureau of Shipping for commercial use.

NUCOTE was conceived in 1969 by E. Rosenberg and engineered by Mike Cook and Ron Reich at the Naval Undersea Center, San Diego, CA. The diving system consisted of a ballasted acrylic sphere suspended by cable from an overhead winch on the NUC offshore Tower (Figure 4). Air was supplied to the sphere by a flexible tube from the tower. The vertical movement of the undersea elevator was controlled from the interior of the sphere by its occupants. The two man capsule was assembled from two acrylic hemispheres fastened to metallic equatorial rings that served as a mechanical equatorial joint (Reference 7). The 54 inch OD flanged hemispheres were freeformed by Fortin Plastics from 2 inch thick sheets that thinned out to 0.91 inches at the poles of hemispheres. The hemispheres were fastened to equatorial steel rings by clamping the acrylic flanges of the hemispheres between the steel equatorial rings and the steel retaining rings bolted to them. The pressure hull saw extensive hydrostatic testing to 100 psi pressure at Southwest Research Institute before it was placed in operation at the NUC offshore tower to a depth of 56 feet in 1973. After years of operation it was taken out of service and placed in storage.

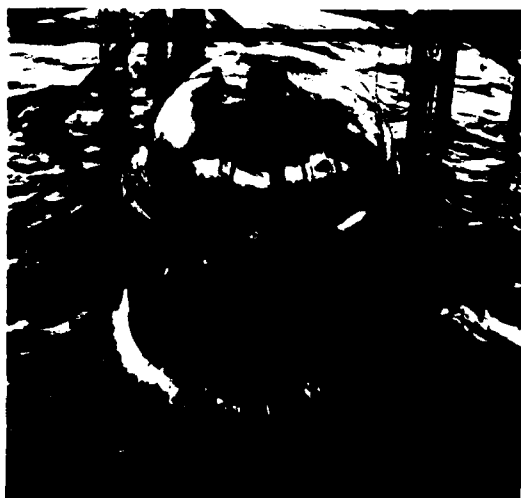


Figure 04. NUCOTE, underwater acrylic plastic elevator installed in the Naval Ocean System's offshore tower at La Jolla, California during 1971.

The first generation of diving systems with acrylic pressure hulls, like flowers in the spring, had a very short operational life, but it alerted the ocean engineering community to (1) the potential of acrylic plastic as an

optically clear structural material and (2) to the operational advantages of panoramic visibility for operators of one atmosphere diving system. The pioneers who conceived these diving systems and personally piloted them during seatrials deserve the thanks of the ocean engineering community as their example widened the operational and engineering horizons for all ocean engineers.

Still, successful as the individual acrylic plastic hulls may been in their application, they were not copied and applied to the following diving systems by other designers. The major reasons for it were (1) shallow design depths and small sizes, resulting from the inability of the chosen fabrication processes to produce larger, thicker spherical shells, (2) absence of published design and test data applicable to larger acrylic spheres and greater depth, and (3) lack of approval for acrylic plastic pressure hulls by the U. S. Navy, American Bureau of Shipping, Lloyd's Register of Shipping, or Det Norske Veritas.

Clearly with this stagnant state of affairs the pioneering momentum of HIKINO, KUMUKAHI, and NUCOTE appeared to have been lost, a flash in the pan, to be followed by years and probably decades of inactivity in the area of acrylic plastic pressure hulls. It remained for DSV NEMO to generate the needed additional momentum that would put acrylic plastic pressure hulls over the top of acceptance barrier in the mind of ocean engineers, and to place acrylic plastic among other, already proven pressure hull materials like steel, aluminum, or titanium.

THE CONCEPT OF NEMO

NEMO (Naval Edreobenthic Manned Observatory) had its origin at the Naval Missile Center, Point Mugu, CA. It is there that Richard G. McCarty and James G. Moldenhauer conceived in 1964 NEMO, a self propelled underwater observatory capable at will to move about in hydrospace until a desirable location was found for detailed study. At that time NEMO would deploy a gravity anchor and by winching itself up or down along the tether it would function as a powered underwater elevator (Figure 5). By maintaining a fixed position with respect to its anchor location, and at the same time being able to traverse vertically the water column above the anchor made NEMO an ideal vantage point for the study of marine animals that periodically migrate upwards or downwards in response to water temperature, phase of the moon, location of the sun, or other environmental factors. Since the quality and quantity of data collected by such an observatory would depend primarily on the ability of the investigators to observe unhindered the hydrospace around the observatory a transparent enclosure would be the ideal solution to this operational requirement.

When the inventors of this concept contacted Corning Glass and Rohm and Haas, leaders in their respective fields, about the feasibility of fabricating a glass or plastic spherical pressure hull capable of

transporting two men to a depth of 1000 feet they were told that such a structure was outside the scope of existing massive glass and acrylic plastic technologies. Only if the Navy was willing to sponsor a multimillion dollar program spanning many years would they promise to deliver such a structure. Since the Navy was not interested in sponsoring a program of such a magnitude the inventors had to regroup and consider other, preferably low cost approaches to fabrication of the 120 inch large transparent spherical pressure hull for their underwater observatory.

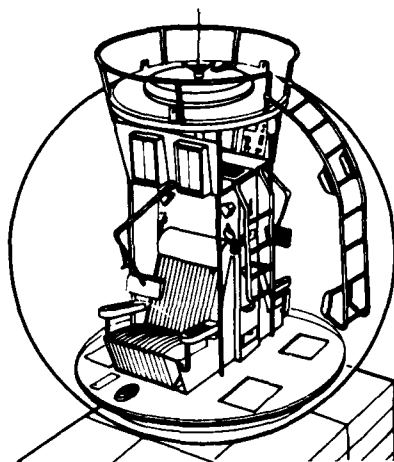


Figure 05. Jim Moldenhauer's concept of NEMO, a 120 inch diameter underwater observatory with panoramic visibility, proposed in 1964.

While researching the problem Moldenhauer ran across two Ordnance Research Laboratory Technical reports published in 1964 by the Pennsylvania State University (Refs. 8,9). In these publications a young structural materials investigator Dr. Jerry D. Stachiw had experimentally shown that (1) acrylic plastic is a suitable engineering material for external pressure hulls, (2) large acrylic pressure hulls can be assembled from small structural modules, (3) the implosion pressure of such hulls did not depend upon the strength of the adhesive bonded joints, provided that the compressive stresses were transferred at right angles across the mating surfaces of the joint, (4) the short term implosion pressure of acrylic hulls can be calculated with classical analytical formulas for buckling of shells if the magnitude of tangential modulus of elasticity is considered to be a function of compressive stress in the shell, and the (5) ideal shapes of structural modules for construction of spherical shells are the equilateral spherical triangle and the spherical pentagon (Figure 6).

Intrigued by these findings the inventors of NEMO tried to contact the author of these reports for further details. To their great surprise he was found nearby at

the Naval Civil Engineering Laboratory in Port Hueneme Co., where he had accepted employment in 1964 after graduation from the Pennsylvania State University. Since Port Hueneme was practically next door to Pt. Mugu a personal meeting was arranged between Moldenhauer, a physicist turned oceanographer and Stachiw, an engineering mechanics graduate turned ocean engineer, that laid the foundation for the engineering development of the NEMO concept. They were soon joined by Kiyoshi Tsuji and Dan T. Stowell, engineers, also employed at the Pacific Missile range. Due to the combined efforts of these individuals the NEMO concept began to be transformed from an idea into engineering design.

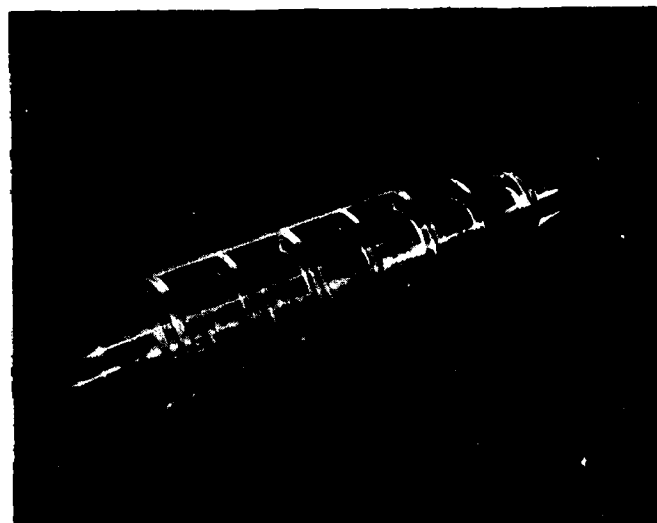


Figure 06. Acrylic plastic housing for oceanographic instrumentation designed for 1000 feet depth by Dr. Stachiw in 1961 while at the Pennsylvania State University. The cylinder is made up of two rib stiffened halfshells sealed by an axial mechanical joint.

Several important problems had to be resolved before NEMO could be launched with a crew in the ocean:

1. A reliable, but economical fabrication technique had to be developed that performed well not only for the construction of scale models, but also for full scale spherical hulls.
2. A proven design for the hull assembly had to be formulated which incorporated into the plastic sphere a metallic hatch for ingress and egress of the crew, and a metallic bulkhead for feedthrough of electrical cables, hydraulic piping and compressed air tubes.
3. The acrylic plastic sphere had to be qualified for manned service to the satisfaction of the Naval Ship Systems Command; the Navy

authorized safety inspector for certification of non-combatant submersibles.

4. Life support, and a propulsion system had to be selected, and mated with the acrylic hull assembly without imposing additional stresses in the acrylic hull.

To facilitate the solution of above problems they were parcelled out to different investigators. Tsuji and Stowell worked on the development of fabrication processes, sizing of life support components and selection of propulsion components. Stachiw devoted his efforts to the design and subsequent evaluation of the model scale and full scale acrylic hull assemblies, and Moldenhauer concentrated his endeavors on the definition of scientific mission objectives for the NEMO.

Each of the components being considered for incorporation into NEMO presented an engineering challenge. The acrylic hull assembly however, posed the toughest challenge of all. Unless the design, fabrication process and structural performance met the U. S. Navy Material Certification Procedures and Criteria Manual for Manned Non-Combatant Submersibles NEMO would never see service in support of Navy missions. Since the Navy had never certified before a diving system with a non-metallic pressure hull the qualification of acrylic plastic as an approved structural material for NEMO would constitute a landmark in the development of Navy's manned non-combatant submersibles. Because the certification of the acrylic hull assembly constituted such a critical element in the realization of the NEMO concept the bulk of available funding during the 1964 - 1969 period was budgeted for the design, fabrication and testing of acrylic hull components.

NEMO PRESSURE HULL DESIGN VALIDATION

As a result of the intensive engineering effort at both NEMO and NCEL a successful hull design was formulated in September 1964, and the first 15 inch OD model scale hull assembly fabricated in January 1965 (Fig. 7). The structural scale model consisted of 12 spherical sectors thermoformed in a female vacuum mold from 0.5 inch thick acrylic discs and subsequently machined into spherical pentagons. Two of the pentagons had beveled openings machined in their center to receive stainless steel hatch and bulkhead assemblies with matching beveled edges. The spherical pentagons, were placed subsequently into an alignment fixture and bonded with solvent injected into the joints with a hypodermic needle. When tested at the NCEL's Deep Ocean Test Facility the 15 x 14 inch spherical hull (1) displayed no permanent deformation after a simulated dive of 5 days duration to 420 feet depth (Figure 8) and (2) it imploded during a simulated dive only after attaining a depth of 3650 feet, predicted by prior analytical calculation of plastic instability.

Encouraged by these results additional twenty 15 x 14 inch scale models were built and tested to destruction under short term, cyclic, and sustained pressure loadings.

These models were identical to the first one except in order to improve the joint quality the gap width between spherical pentagons was increased to 0.125 inches. This gap was subsequently covered with adhesive backed aluminum tape, and filled by gravity through a funnel with self polymerizing adhesive cement (Reference 10).



Figure 07. Components of the 15 x 14 inch structural scale model of acrylic plastic pressure hull for NEMO designed by Dr. J. D. Stachiw at the Naval Civil Engineering Laboratory, and fabricated under the supervision of K. Tsuji at the Naval Missile Center, Pt. Mugu, CA in 1964.

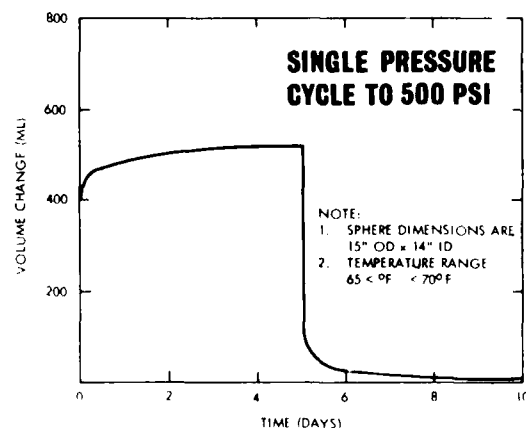


Figure 08. Volume displacement plot generated during the hydrostatic testing of NEMO scale model. Note that the pressure hull returns to its original shape following depressurization and relaxation.

After two years of pressure testing twenty spherical 15 x 14 inch scale models that required 3000 hours of pressure vessel time the NEMO type design of acrylic plastic spheres was considered to be ready for transitioning to full scale construction. The experimental data showed that the structural behavior of acrylic spheres with less than 0.5 percent spherical deviation and 3 percent local thinning out due to thermoforming was repeatable. The major findings were:

- a. The short term implosion depth can be predicted in advance on the basis of analytical calculations.
- b. The time dependent implosion at any dive depth can be predicted far in advance on the basis of an empirically generated linear plot on log-log coordinates of implosion pressure versus duration of loading.
- c. The crack free cyclic fatigue life is in excess of 1000 dives if the maximum dive depth is less than 33 percent of the short term implosion depth and the relaxation periods between individual dives equal, or surpass the duration of individual dives.
- d. The effect of temperature on implosion depth can be predicted from empirically generated graphic plot relating temperature to implosion pressures.

The fabrication of the full scale NEMO, hull was initiated in 1967 and completed in 1968 at NMC Point Mugu, CA. The outside diameter of the sphere was 66 inches, the largest size that could be achieved by assembling 12 pentagons formed and machined from standard 48 x 60 inch acrylic sheets with 2.5 inch nominal thickness (Fig. 9). The design of the full scale hull assembly and the fabrication procedures were the same as in the scale model hulls to insure reproducibility of structural performance (Ref. 11).

The quality assurance procedures instituted during the fabrication produced a hull whose sphericity and uniformity of thickness matched that of the 15 inch scale models (Fig. 10). The thinning out due to thermal forming was less than 2 percent and the deviation in sphericity less than 0.5 percent at the center of each pentagon. The completed sphere deviated less than 0.5 percent from the ideal 33 inch radius of sphericity. The fit between the machined metallic components and the acrylic hull was very good; the mismatch between the bevel angle on the hatch and the opening in the hull was less than 0.5 degree. The resulting 66 inch hull assembly was in all respects a scaled up copy of the 15 inch model (Figure 9), and its structural performance, provided there was no material scaling factor involved, (like for example in glass), would be identical to that of the scale models. If the test results supported this hypothesis the last obstacle in the mind of the safety review members would be removed to the utilization of acrylic plastic in the construction of pressure hulls for manned diving systems.

After being pressure cycled 104 times in the 500 to 1140 psi range the 66 inch NEMO was imploded at 1850 psi during a simulated rapid descent at 220 feet/second rate. This test confirmed the basic postulate of the material qualification program:

Experimental data generated with 15 inch scale model spheres is directly applicable to 66 inch full scale spheres (i.e. large thick acrylic spheres behave identically like small, thin acrylic spheres with the same t/D_o ratio).

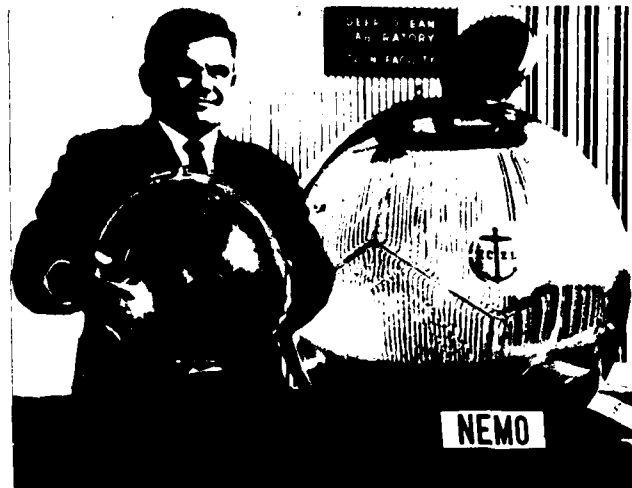


Figure 09. Full size 66 x 51 inch NEMO hull fabricated by the Naval Missile Center in 1967 and tested to implosion at the Naval Civil Engineering Laboratory in 1969 under the supervision of Dr. Stachiw.



Figure 10. Checking the dimensions of a finished 66 inch diameter NEMO hull.

NEMO DIVING SYSTEM

As soon as the pressure testing of the first full scale NEMO pressure hull was completed a patent disclosure was filed (Fig. 11) and proposals were submitted to various Navy Bureaus (present name: Commands) for funding of the NEMO diving system. Only the U.S. Navy Bureau of Yards and Docks (present name NAVFAC; Naval Facilities Engineering Command) promised financial support, provided that (1) the diving system is modified to serve as a diving superintendent's office on underwater construction sites employing divers (Figure 12) and (2) the pressure hull assembly is standardized to serve as a self contained multipurpose one atmosphere cockpit for a variety of underwater construction equipments (Figures 13).

The contract for the construction of one NEMO system for NAVFAC was awarded in 1969 to the Southwest Research Institute, and a separate contract for fabrication of three 66 x 51 inch acrylic pressure hulls to Swedlow Inc. One of those hulls was slated for incorporation into NEMO system, one for cyclic pressure testing at NCEL, and one was to be delivered to Naval Undersea Center (present name NOSC; Naval Ocean Systems Center) for incorporation into the submersible MAKAKA, the successor to HIKINO (References 12,13,14,15,16).

United States Patent

III 3,527,184

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(21) Appl. No. 964,696
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(43) Published Sept. 8, 1970
(73) Assignee: the United States of America as represented
by the Secretary of the Navy

(54) References Cited
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2,391,940 8/1942 Babcock 114/16
2,294,296 8/1942 Hansen 114/16X
Primary Examiner - Benjamin A. Borchelt
Assistant Examiner - Thomas H. Webb
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(54) EMBODIMENT MANNED OBSERVATORY
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(50) Field of Search 114/16,
61/69 220.3

ABSTRACT: A self-contained positively buoyant observatory having panoramic visibility. It is formed of transparent wall material. Special strengthening members are provided and it is adapted to house personnel and equipment for sustained marine observation. It is normally anchored to the ocean floor. An anchor line is connected to a winch within the observatory and permits the same to be moved up or down at the discretion of the occupants.

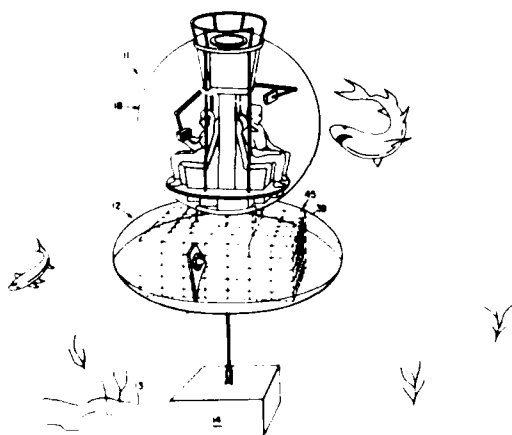


Figure 11. Patent granted for NEMO concept.

To provide the forthcoming NEMO diving system with qualified operators NCEL initiated immediately a training program for NEMO pilots, patterned after NASA's successful training program for astronauts. Four NEMONAUTS were chosen from a dozen applicants for the training program; their training extended over one year (Fig. 14). The characteristics of the NEMO diving system for which the NEMONAUTS were training are described below:

CHARACTERISTICS OF NEMO HULL

Outside diameter 66 inches
Inside diameter 61 inches
Wall thickness 2.5 inches
Weight (with steel hatches) 1500 lbs.
Displacement 87.5 cu. ft.
Operational depth 600 ft.
Design depth 1000 ft.
Proof depth 1120 ft.
Implosion depth 4150 ft.
Material acrylic plastic
MIL P-5425

GENERAL CHARACTERISTICS

OPERATING DEPTH
600 feet
DIMENSIONS
width-78", height-110"
WEIGHT
8000 lbs in air
CREW
1 operator, 1 observer
PRESSURE HULL
acrylic plastic sphere
outside diameter-66"
wall thickness-2.5"
LIFE SUPPORT
64 man-hours
POWER
120V DC and 24V DC
150 amp-hours (main battery)
PAYLOAD
Average crew plus 450 pounds
VERTICAL MOBILITY
2 hp winch and 500 lb anchor
speed - 30 to 60 fpm
HORIZONTAL MOBILITY
two 1½-hp hydraulic motors
speed - 0 to 3/4 knots
LIGHTING
two 500-watt, two 750-watt
BUOYANCY CONTROL
open air ballast tank and 371 scf of air
COMMUNICATIONS
surface - HF radio
subsurface - underwater telephone (8.1 kHz)
WORK CAPABILITY
underwater hydraulic and electrical
connectors for divers
SUPPORT FACILITIES
28' trailer with support van

There were only three major departures in NAVFAC NEMO from the original NEMO concept proposed by the Naval Missile Center in 1965 (Ref. 10). The diameter was 66 instead of 120 inches, and as a result of the reduced diameter the two occupants had to sit side by side, instead of back to back. The life support duration was shortened from 100 to 32 hours as the function of the diving system shifted from a long term in situ oceanographic observatory to a short term diving supervisors observatory. Finally, the diving system was equipped with external hydraulic and electrical connectors for powering of diver operated power tools at the work site in the vicinity of NEMO (Figure 15).

The NAVFAC NEMO was officially launched in May 1970 by Rear Admiral Johnson amid great ceremonies attended by representatives of U.S. ocean engineering community at Freeport, Bahamas. After several preliminary dives NEMO reached 600 ft. depth piloted by E. Briggs and L. Poirer of Southwest Research Institute.

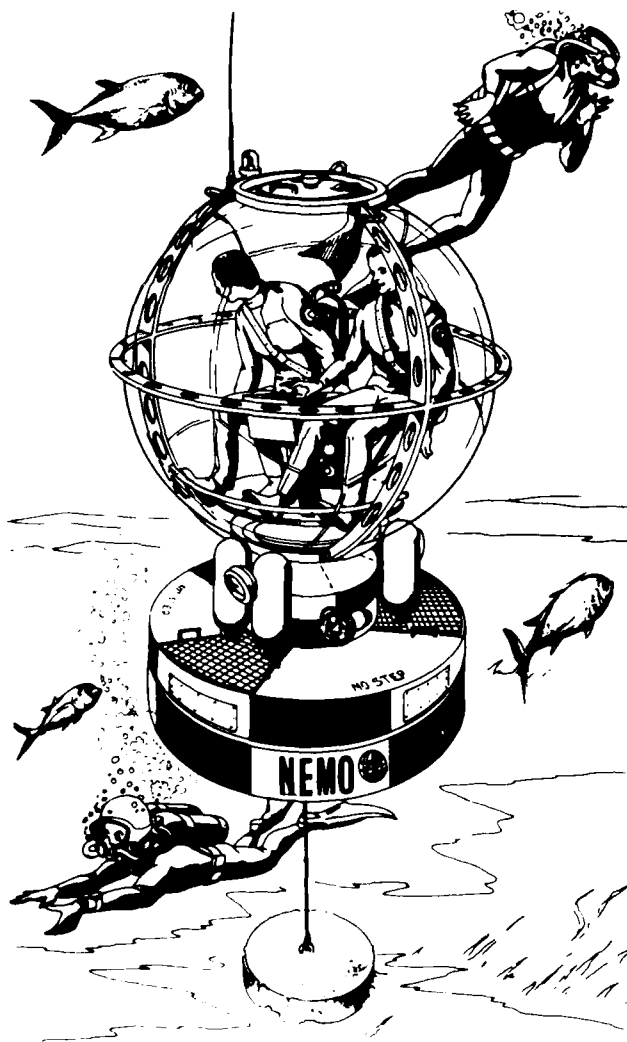


Figure 12. The NEMO concept funded for construction by the Naval Facilities Engineering Command

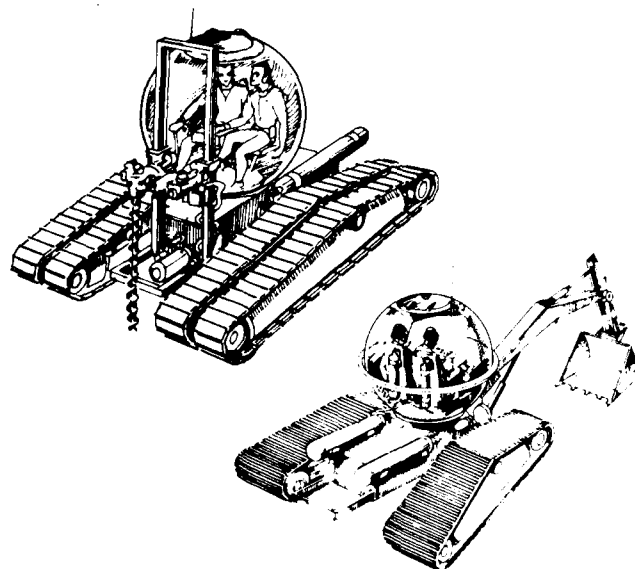


Figure 13. The concept of standardized 66 inch diameter one atmosphere acrylic plastic cockpit integrated with proposed undersea earth moving equipment.



Figure 14. Naval Civil Engineering Laboratory's NEMONAUTS; Lt. R. E. Elliott, R. F. Crowe Jr., P. R. Rockwell, and M. R. Snoey (from left to right).

During the remainder of the two week long seatrials NEMO dove repeatedly to 600 feet under the charge of four NCEL trained NEMONAUTS without any mishap. The diving operations were supervised by CDR Noel Brady, assisted by LCDR Donald Black and Lt. Ross Saxon from SUBDEVGRU ONE, San Diego.

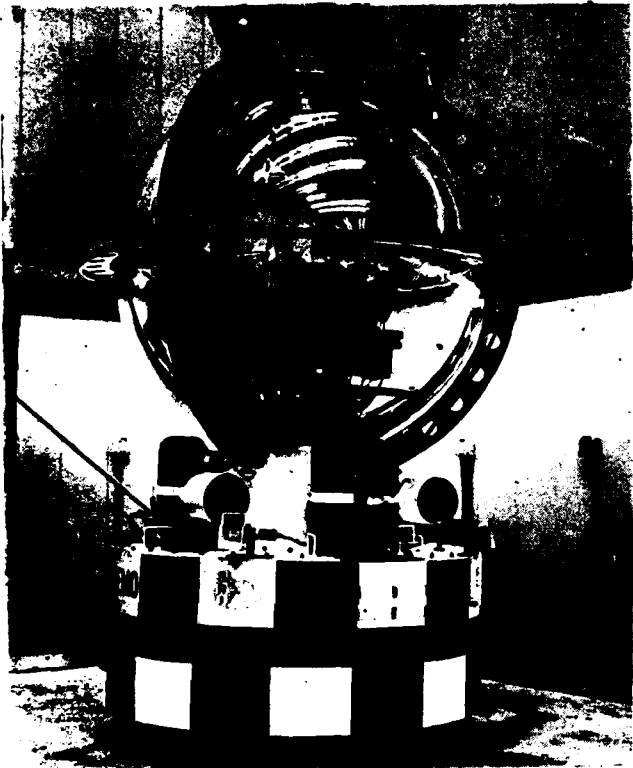


Figure 15 The 66x51 inch acrylic plastic hull installed in the NEMO submersible fabricated at SWRI under supervision of E. Briggs.

The sea trials off Freeport, Bahamas were followed in July 1970 by material certification dives off Port Hueneme, CA. As a result of the extensive test and evaluation program the U.S. Navy Ship Systems Command certified on 12/15/1970 DSV (Deep submergence Vehicle) NEMO as materially adequate for Navy service to 600 ft. depth. The certification was renewed thereafter annually (Figure 16). DSV NEMO saw extensive diving service from 1970 to 1980 during which it experienced 671 dives in the 50 to 600 feet range without any visible sign of material fatigue in the acrylic pressure hull assembly.

The other NEMO hull, which was incorporated by Doug Murphy into the MAKAKAI submersible at NUC Hawaii Laboratory was also certified by the U.S. Navy for 600 feet depth service in 1971. It saw extensive service in support of the sea animal research and training program at the NUC Hawaii Laboratory (Figure 17). It was removed from service in 1976 and placed on permanent display at Sea World, San Diego.

After 10 years of service NEMO was decommissioned in 1980 as part of an economy measure from Navy service and placed on display at the Naval Ocean Systems Center. Specimens taken from the acrylic hull after its decommissioning showed that after 10 years of service in marine environment the photochemical deterioration in the acrylic material had penetrated less than 0.040 inches deep (Reference 18). Since the thick hull material sees mostly only membrane compressive stresses during a typical dive the deterioration of a thin layer on its outside surface would not affect its safe maximum operational depth, particularly in view of the safety factor of 7 used by NAVSHIPS in

U.S. NAVY SAFETY CERTIFICATION FOR NON-COMBATANT SUBMERSIBLES		
1. NAME OF SUBMERSIBLE NEMO	2. BUILDER South West Research Institute	3. TYPE Oceanographic Research Vehicle
4. DISPLACEMENT 7850	5. REGISTRATION NO. N/A	6. AUTHORIZED DEPTH 600 FT.
7. AUTHORITY AND BASIS FOR ISSUANCE: This certificate is issued pursuant to the current SECNAVINST 0294.1 and certifies that, as of date of issuance, the submersible to which issued, has been inspected and found to be materially adequate as described in the MATERIAL CERTIFICATION PROCEDURES AND CRITERIA MANUAL FOR MANNEED NON-COMBATANT SUBMERSIBLES.		
8. TERMS AND CONDITIONS: Unless sooner surrendered, suspended, revoked, or a termination date is otherwise established by the Naval Ship Systems Command, Washington, D.C., this certification is effective until it expires (see date below), as long as the submersible operates within the authorized depths noted in item 6 above, and preventive maintenance and alterations are performed in accordance with the MATERIAL CERTIFICATION PROCEDURES AND CRITERIA MANUAL FOR MANNEED, NON-COMBATANT SUBMERSIBLES.		
DATE CERTIFICATE ISSUED 13 February 1973	DATE CERTIFICATE EXPIRES 60,000 13 Feb 1974 or dive-ft.	NAVSHIPS LTR FILE REF Ser 665-425
BY AUTHORITY OF NAVY SECRETARY <i>R. S. Wilson</i>		NAVSHIPS LTR. DATE 27 Feb 1973
NAVSHIPS 9296/4 (10-67)		NOTE: VOID IF ALTERED, DEFACED OR EXPIRED

Figure 16. U. S. Navy Certification for DSV NEMO, awarded originally on December 1970 and renewed thereafter on an annual basis to 1980.

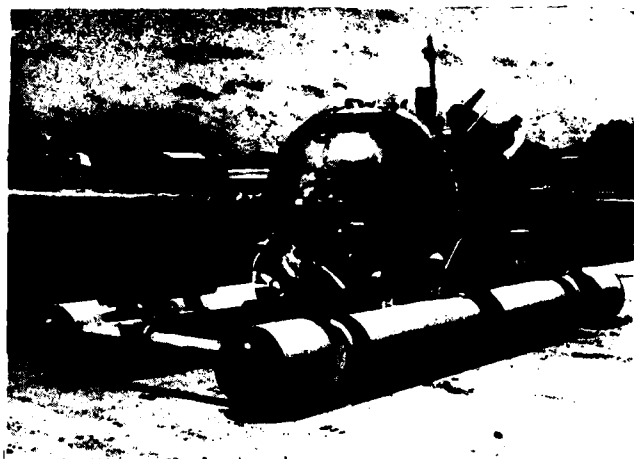


Figure 17. The 66 x 61 inch acrylic plastic hull after installation in the MAKAKAI submersible fabricated under the supervision of D. Murphy in 1971 at the Hawaii Laboratory of the Naval Undersea Center.

establishing the overly conservative safe design depth of 600 feet. One of the valuable side benefits of the 10 years of NEMO's satisfactory service was the change in Navy's thinking about the magnitude of safety factors; a safety factor of 4 is considered now to be totally adequate for acrylic pressure hulls.

The decommissioning of NEMO in 1980 signaled the closing of the pioneering, and the beginning of the application epochs for acrylic submersibles. Prior to NEMO acrylic submersibles were considered on par with hot air balloons at county fairs; thrilling for the pilots, but of no commercial value to the industry. In the short time span between NEMO certification in 1970 and its decommissioning in 1980 the stature of acrylic submersibles grew from interesting, but nevertheless exotic freaks to accepted work horses of the ocean engineering community.

IN THE FOOTSTEPS OF NEMO

NEMO was followed by the Johnson Sea Link I, a unique submersible designed by Mr. E. Link for the Smithsonian Institution (Figure 18). It combined the advantages of panoramic visibility, provided by the acrylic spherical hull, with the lockout capability, provided by the aluminum cylindrical hull. The acrylic spherical hull, also engineered by Stachiw, was of the same size, design (Figures 19 and 20) as NEMO hull, except that aluminum was used in hatches, a polycarbonate gasket was placed between the metallic components and the acrylic hull and the wall thickness was increased to 4 inches, giving the Johnson Sea Link I a design depth of 3000 feet (References 19 and 20).



Figure 18. The 66 x 58 inch acrylic plastic hull after installation in the Johnson-Sea-Link #1 submersible designed by E. Link and fabricated in 1971 under the supervision of R. Dolan at the Harbor Branch Foundation.

To facilitate the certification of this submersible the Naval Undersea Center conducted a testing program on one full scale and four 15 x 13 inch scale models fabricated by Swedlow Inc. in the same manner as the full scale hull. The test results validated the 3000 design depth of the acrylic hull. The 66 x 58 inch acrylic hull withstood 24 hour long pressure cycles to 2000, 3000, and 4000 feet without any permanent deformation in the acrylic or metallic components. One of the 15 x 13 inch scale models was imploded at 10,000 feet depth, while the remainder of the 15 x 13 inch spheres withstood 1000 typical simulated dives to 3000 feet depth without initiation of any cracks in the hull (References 21). The testing program was concluded by imploding the scale models under dynamic pressure loading generated by underwater explosions (References 22).

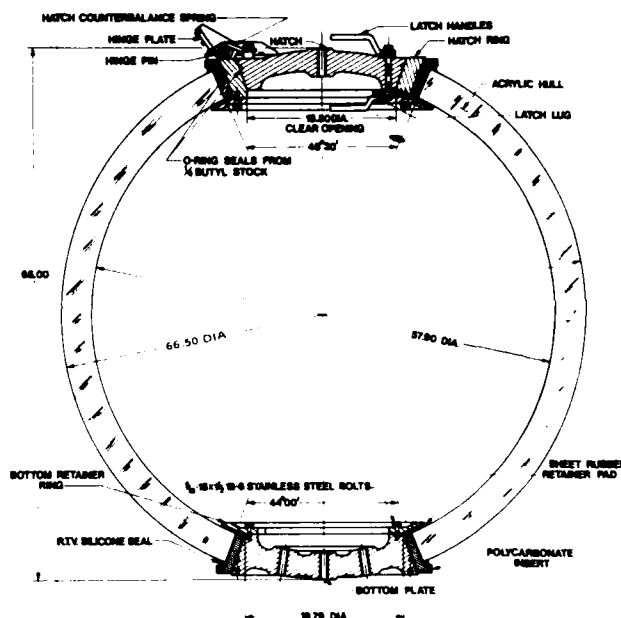


Figure 19. Typical features of the NEMO type acrylic plastic hull design. The dimensions shown are for the 66 x 58 inch hull with 3000 feet design depth.

The submersible was certified by the American Bureau of Shipping to 1000 feet depth in 1971 and to 2640 feet depth in 1983. The submersible is still in service, a veteran of more than 1000 dives in the ocean.

Even though the construction of Johnson Sea Link I conclusively showed that the fabrication technique developed for the 2.5 inch thick 66 inch diameter NEMO hull was also applicable to the 4 inch thick 66 inch diameter JSLI hull it also showed that this construction technique was severely circumscribed by several limitations characteristic to this type of construction technique.

1. Thermal forming of spherical pentagons with t/Ro ratios in excess of 0.15 introduced into the external surface of pentagons unacceptably high residual tensile stresses that with time initiated crazing of the surface.
2. The size of the spheres was limited to 66 inches, the largest size that could be assembled by thermoforming of pentagons cut out of largest available 4 inch thick sheets cast from monomer resin.

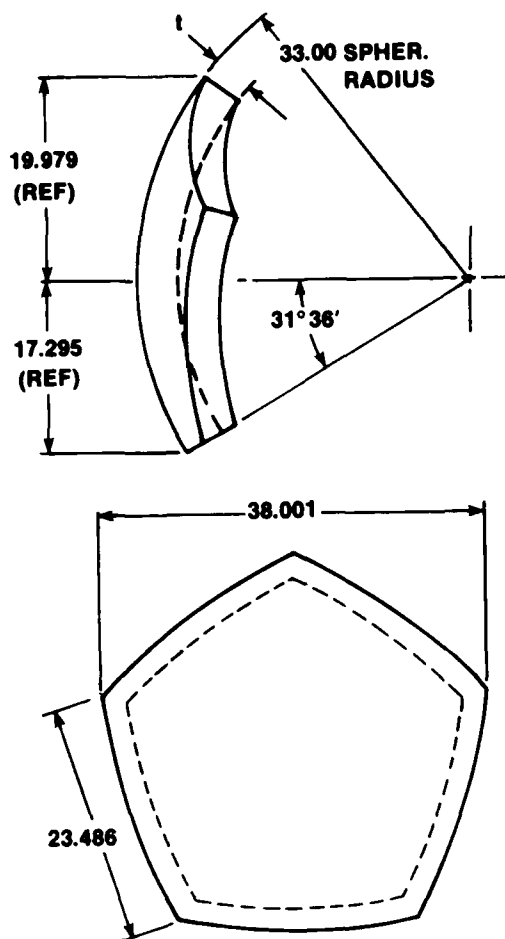


Figure 20. Typical dimensions of spherical pentagons used in the assembly of 66 inch diameter NEMO type acrylic plastic hulls.

The effect of these limitations was that for acrylic plastic spherical hulls with 66 inch outside diameter, fabricated by bonding of 12 spherical pentagons, the 3000 foot design depth was probably the maximum design depth attainable in that size. This technological barrier to the orderly development of large and deeper diving acrylic plastic spherical hulls was early recognized by Stachiw and

brought to the attention of Dr. W. McLean, Technical Director of Naval Undersea Center (NUC) and E. Link, Director of the Harbor Branch Foundation (HBF), both enthusiastic supporters of the transparent hull technology (Figure 21)



Figure 21. Dr. W. B. McLean, Technical Director of the Naval Undersea Center, and E. A. Link, Vice President of the Harbor Branch Foundation reviewing in 1973 with Bruce Beasley, owner of Polymer Products, the potential of his slush casting process for casting of large hemispheres

The solution to this problem was suggested by Bruce Beasley, a noted sculptor who specialized in massive monolithic acrylic sculptures cast in his own studio in Oakland, CA. He proposed in 1969 that the acrylic spheres be fabricated by casting of monolithic spherical shells, or if this was too expensive, by joining of hemispherical shells cast inside permanent metallic molds in his own shop. His suggestion was accepted and with funding provided jointly by NOSC and HBF he developed a technique for casting of hemispheres in permanent steel molds from a carefully compounded mixture of methyl methacrylate monomer resin and polymerized methyl methacrylate powder.

The pre-polymerized methyl methacrylate powder dissolved in the monomer resin minimized shrinkage and exothermic reaction during the polymerization cycle. The addition of polymerized powder to the monomer resin gave it the consistency of slush ice and as a result of it this type of casting technique was referred to as slush casting. This mixture turned after several hours at room temperature into a firm jelly which after application of heat in a pressurized autoclave became crystal clear, hard acrylic plastic. The application of pressure in the autoclave served to suppress the formation of gas bubbles inside the jelly like mixture during exothermic reaction.

There appeared to be no physical limit on the thickness of the sphere cast by this process, and the only limit on the size of the sphere was the size of available autoclaves in which the molds with the casting mixture had to be placed for polymerization. The required validation of slush casting technique was performed in 1974 on 18 inch OD x 10 inch ID hemispheres which were subsequently bonded together by Stachiw into spheres and subjected to hydrostatic testing. The results of the tests performed at the Southwest Research Test Institute were satisfactory (Reference 23), and Beasley was given authorization to proceed with the casting of several 66 inch x 58 inch NEMO spheres (Figure 22). Two of these spheres were delivered to HBF for incorporation into submersibles and one was delivered to NUC for test and evaluation under hydrostatic loading (Reference 24).

The results of hydrostatic test performed in 1975 on the cast 66 x 58 inch sphere at the Southwest Research Institute were satisfactory. The pressure hull successfully withstood 24 hours long simulated dives to 2000, 3000 and 4000 feet without permanent deformation after 24 hours long relaxation periods following each dive. It imploded only after 13 minutes of sustained pressurization during a simulated dive to 9000 feet. The testing of the full scale hull proved conclusively that (1) the structural performance of slush cast spherical hulls is identical to thermoformed spherical hulls, and similarly that (2) the structural performance of full scale slush cast spherical hulls is identical to that of scale models.



Figure 22. The first successful pair of 66 x 58 inch hemispheres slush cast by Bruce Beasley for the Naval Undersea Center in 1974. Mike Stachiw is assisting Beasley during the critical bonding of the equatorial joint.

Now there was no further doubt that the slush casting process produces acrylic plastic pressure hulls with the same structural performance as thermoformed hulls, and therefore all the design criteria generated with thermoformed spheres during the developments of NEMO design apply also to the spheres fabricated by slush casting. The slush casting technique made it now feasible for the first time in ocean engineering history to fabricate economically spherical pressure hulls of any desirable thickness or size, the only limitations being the imagination of the designer and the pocketbook of the customer.

Since the slush casting technique lends itself also to casting of acrylic plastic shells of any shape, pressure hulls can be now cast in any imaginable configuration. To date the slush casting technique has been already employed to cast cylinders and paraboloids of revolution. There is no doubt it will be used in the future to cast ellipsoidal and toroidal pressure hulls; shapes that previously could never be thermoformed successfully (Reference 25).

ACCEPTANCE OF ACRYLIC PLASTIC FOR CONSTRUCTION OF DIVING SYSTEMS

As a result of NEMO's certification by the U. S. Navy in 1970 the American Bureau of Shipping and Det Norske Veritas (U.S. and Norwegian based ship classification societies) took administrative steps to incorporate acrylic plastic into their rules for construction and classification of underwater systems and vehicles. The American Society of Mechanical Engineers, Pressure Technology, Codes and Standards under the leadership of M. R. Green recognized immediately the emergence of acrylic plastic technology for construction of pressure hull components and formulated in 1971 the Safety Code Committee on Pressure Vessels for Human Occupancy (PVHO) to formulate design rules for its use in manned diving systems.

In 1977 ASME published ANSI/ASME PVHO-1 Safety Standard for Pressure Vessels for Human Occupancy which includes a section on the application of acrylic plastic to pressure vessel construction. The Coast Guard, U. S. Department of Transportation referenced ANSI/ASME PVHO-1 in its 1978 Rules and Regulations for Commercial Diving Operations, immediately followed by the American Bureau of Shipping which also referenced ANSI/ASME PVHO-1 in their 1979 Rules for Building and Classing of Underwater Systems and Vehicles. Foreign classing societies also included acrylic plastic in their Rules of Construction of Diving Systems so that by 1980 the acceptance of acrylic plastic pressure hulls and pressure hull components was complete. Thus, in one short decade from 1970 to 1980 the acrylic plastic pressure hull technology incorporated in NEMO transitioned from the experimental to the proven state of pressure hull construction. From that period on there were no further administrative obstacles in the path of acrylic pressure hull development and utilization in underwater vehicles and diving systems.

THE LEGACY OF NEMO PROGRAM

Twenty years have passed since the initiation of NEMO program by the U. S. Navy at the Naval Civil Engineering Laboratory Port Hueneme, CA and the Naval Missile Center, Point Mugu, CA. The program achieved at a very modest cost its original objective; the design, fabrication, and operation of a manned, one atmosphere underwater vehicle/observatory with panoramic visibility for 600 feet depth. In addition, it not only qualified acrylic plastic for construction of external pressure hulls, but also developed a novel fabrication process that allows the casting of acrylic plastic structural components of any size, thickness, or shape.

The number of acrylic plastic submersibles operating today is fairly modest (i.e. Johnson Sea Link #1, Johnson Sea Link #2 Checkmate and Deep Rover). The primary reason for their modest number is the depressed state of offshore oil production industry. But even so the operational depth reached by acrylic plastic submersibles (Figures 23, 24) has progressed steadily from the historic dive to 600 feet in 1970 by NEMO to the 3000 feet dive in 1986 by Deep Rover (Reference 26). There is no doubt that the depth capability and size of acrylic pressure hulls will expand further, a spherical pressure hull with 108 inch diameter has been already designed for 8000 feet depth, scale models of that hull have been built, and a hydrostatic pressure cycling program has been initiated at the Harbor Branch Foundation at Link Port, Florida (Reference 27).

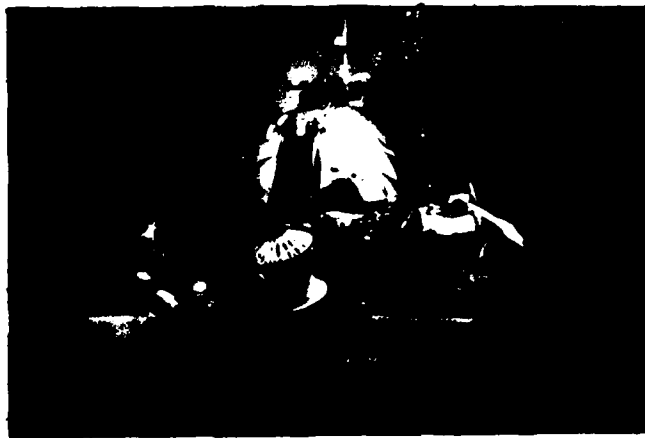


Figure 23.. One man minisub Deep Rover designed by Graham Hawkes and fabricated by Deep Ocean Engineering Inc., in 1984. The 63 x 53 inch slush cast acrylic plastic hull provides the 6800 lb. submersible with 3280 feet operational depth capability.

At what depth the development of spherical acrylic plastic hulls will stop is

hard to predict, but in all likelihood it will reach a limit at 10,000 feet, as beyond this depth the weight to displacement ratio and optical effects of the very thick hulls will make the acrylic plastic hull operationally unacceptable (References 28,29,30,31).

For depths beyond 10,000 feet the spherical hulls will have to be fabricated from glass or transparent ceramic possessing compressive strength in excess of 100,000 psi. To qualify those materials for construction of manned diving systems calls for initiation of a second NEMO program. But this is yet another story to be written in the future by ocean engineers dedicated to exploration of hydrospace for scientific knowledge and economic benefits to the nation.



Figure 24. Slush cast hemisphere used by Mark Stachiw in 1984 for assembling a 18 x 12.85 inch scale model of acrylic plastic hull with 8000 feet design depth for the Harbor Branch Foundation.

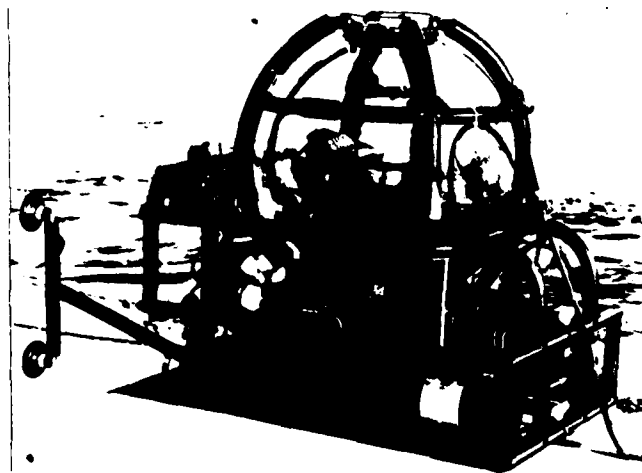


Figure 25 Tethered submersible CHECKMATE with 81 x 74.8 inch acrylic plastic hull for 1000 feet depth. Launched in 1979 off Norway by Mollerodden A.S.

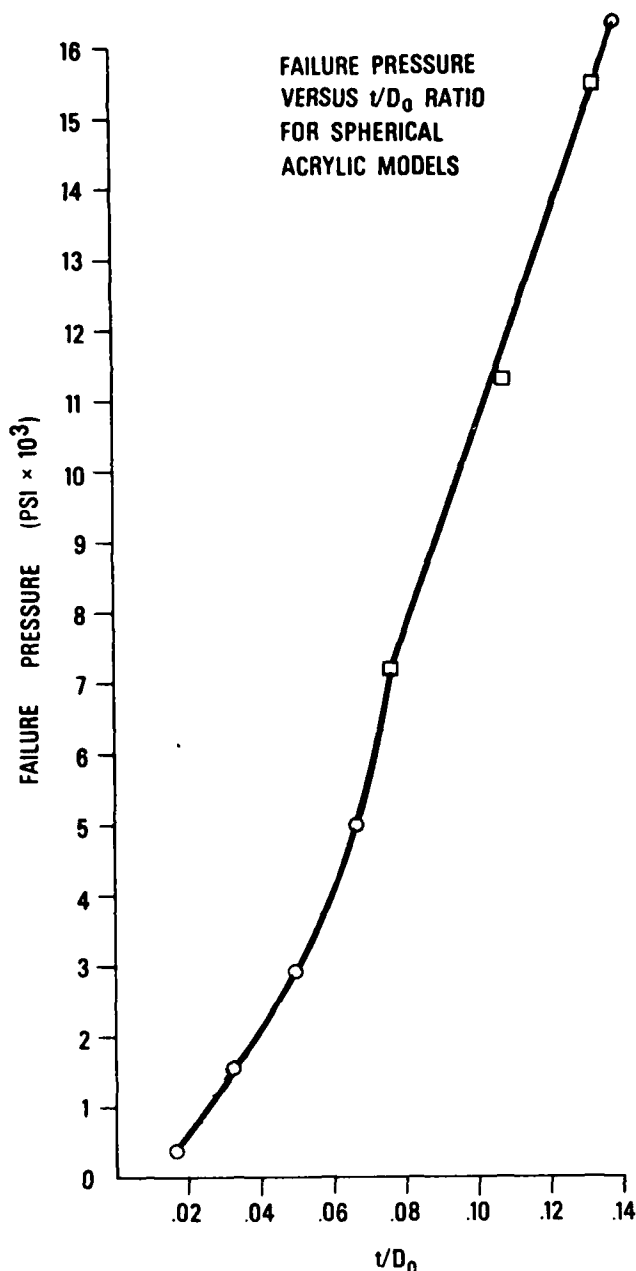


Figure 26

Critical pressure of acrylic plastic spheres pressurized to implosion at 100 psi minute rate in 75 degree Fahrenheit ambient environment. Spheres with $t/D = 0.22$ have been pressurized to 20,000 psi, the maximum available pressure, without imploding. Applying the conversion factor of 4 recommended by ASME PVHO it appears feasible to reach 10,000 feet depth in a submersible equipped with acrylic plastic spherical pressure hulls.



Figure 27 Typical arrangement for hydrostatic testing of acrylic plastic spherical hull scale models. The spherical hulls are suspended from the pressure vessel and closure by means of a pipe open at one end to the interior of the hull and on the other end to the exterior of the vessel. This tube served as pressure resistant conduit for instrumentation wires and relief for internal pressure buildup in the sphere.

The specimen shown here is a 18x12.85 inches acrylic plastic sphere being tested by Mark Stachiw and Karl Hilton at NCEL's Deep Ocean Test Facility. The sphere imploded at 16,000 psi under short term pressurization in 65 degree F water, indicating that cyclic fatigue life will probably exceed 1000 pressurizations to 4000 psi.

CONVERSIONS

psi = 2.247 feet seawater depth
psi = 0.6849 meters of seawater depth
psi = 6.895 kPa
psi = 0.07031 kg/square centimeter
inch = 2.54 centimeters
pound = 0.454 kilograms

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